Thermophysics issues relevant to high-speed Earth entry of large asteroids

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The Big Picture

• What size asteroid?
  • Shape and size

• (of) What spectral type?
  • Stony (S)
  • Stony-iron (X)
  • Iron (M)

• (at) What entry conditions?
  • Entry velocity ($u_0$)
  • Entry flight path angle ($\gamma_0$)

• (causes) What kind of damage on the planet via …
  • Airburst, or Cratering, or Tsunami?

Capsule entry physics has some things in common with meteor physics, but approaches to the problem are different – prediction vs reconstruction
Bringing reliable predictive capabilities to bear on meteoroid entries is the focus of efforts
Entry Capsules vs. Meteors

- **Stardust [1]**
  - Size was 0.8 m (dia)
  - Velocity < 13 km/s
  - Low ballistic coefficient

- **Meteoroids/Asteroids [2]**
  - Sizes >> 1 m (dia)
  - Velocities > 12 km/s
  - High ballistic coefficients
  - High stag. pressures
  - High Reynolds numbers

MORP = Meteorite Observation & Recovery Project [3,4]

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**References:**

Flight Space

- Assume entry interface (EI) at 100 km
  - If $Kn \leq 0.005$ is a criterion for using a continuum CFD approach, then min. diameter of a sphere is 28.4 m
- Computations performed for various size (hemi)spheres at conditions within the FLIGHT SPACE shown

References:
Motivation

• Can some of the modern computational analysis tools used in heatshield design be used (repurposed?) for simulation of asteroid entries?

• For various classes of asteroidal materials, can we build/develop models for:
  • Aero/aerothermodynamics
  • Material thermal response?
  • Material structural response, including fragmentation?
  • Energy deposition along meteor trajectory in the atmosphere?

• How much would the results of these models differ from, and improve upon, those obtained from the equations of meteor physics?
Mass Loss – Single Body

Mass loss

\[
\frac{dm}{dt} = \frac{1}{2} a u^3 C_D A
\]

Luminosity

\[
I = \frac{dE}{dt} = \frac{1}{2} u^2 + 1 \frac{1}{2} a u^3 C_D A
\]

\[ \frac{C_H}{C_D Q} \]

\[ \rho_a \text{ Ambient density} \]
\[ Q \text{ Heat of ablation} \]
\[ u \text{ Meteor velocity} \]
\[ m \text{ Meteor mass} \]
\[ C_H \text{ Heat transfer efficiency} \]
\[ t \text{ Time} \]
\[ A_m \text{ Cross sectional area} \]
\[ \sigma \text{ Ablation coefficient} \]
\[ C_D \text{ Drag coefficient} \]
\[ \tau \text{ Luminous efficiency} \]

- \( C_H \) is \textit{efficiency} of conversion of freestream energy into heating of surface
- \( Q \), heat of ablation, is a big source of uncertainty
  - Need to understand energetics of melt vs. vaporization
  - Exploratory test on meteoritic materials performed at LHMEL [1]
    - Surface irradiation with 1.07 µm fiber laser
    - 2\textsuperscript{nd} round of testing of H chondrites scheduled for 2016
- \( \tau \) is fraction of deposited energy captured as visible light on a detector

Reference:
Objectives

• To estimate heat transfer efficiency, $C_H$
  - (Hemi)spherical shape is the focus – diameters ranging from 1 m to 300 m
  - Entry velocities ranging from 12 km/s to 30 km/s
  - Stagnation pressures ranging from 0.3 bar to 300 bar

• To estimate energy radiated (to ambient air)
  - Energy deposition (partly)

• To explore influence of surface blowing on flow characteristics
  - Equivalence to surface recession?

• To explore general flow characteristics of multiple bodies in proximity
  - Shock-shock interactions and their aero/aerothermal effects
  - How fragments interact with each other
Modeling Tools

• Flow computations (\textit{DPLR}) [1]:
  • Navier-Stokes (axisym or 3D) calculations for body in a fixed frame of reference
  • Turbulent flow of 11-species air (N\textsubscript{2}, O\textsubscript{2}, NO, N\textsubscript{2}\textsuperscript{+}, O\textsubscript{2}\textsuperscript{+}, NO\textsuperscript{+}, N, O, N\textsuperscript{+}, O\textsuperscript{+}, & e\textsuperscript{−})
    – Include N\textsuperscript{2+}, O\textsuperscript{2+}, N\textsuperscript{3+}, and O\textsuperscript{3+} for freestream velocities > 20 km/s
  • Gas phase rate chemistry

• Radiation computations (\textit{NEQAIR}) [2]:
  • Line-by-line simulations with temperatures & number densities from flow solutions
    – Includes discrete transitions (atomic lines – nosecap, and molecular band systems - wake) and continua (bound-free & free-free)
  • Decoupled from flow computations (adiabatic inviscid shock layer assumption)

• Flow & radiation fields are tightly coupled with material thermal response
  • \textit{DPLR-NEQAIR} coupling methodology currently under development
  • Material response code, \textit{ICARUS}, is also under development

References:
Modeling Assumptions

- **Assumption #1**: The meteor body *does not* ablate
  - No shape change
- **Assumption #2**: The meteor body *does not* cool by re-radiation (cold wall)
  - Allows application of physically meaningful surface boundary conditions, i.e., catalytic recombination of species (atoms and their ions)
- **Assumption #3**: No blockage by vapor phase of meteoritic material
  - Need material thermal response model
  - Need gas phase thermodynamic and transport properties of blown species

Assumptions provide upper bound on heating (convective and radiative)
Quantification will require coupled computations!
Computational Process

Flow computation
\textit{DPLR} code

\[ C_H = \frac{2}{3} \int_0^1 q(\theta) \sin \theta \, d\theta \]

\[ q(\theta) = q_{\text{Turbulent}}(\theta) + q_{\text{Nonadiabatic}}(\theta) \]

Tauber-Wakefield radiation cooling correlation \cite{1}

Scaling Laws

Radioactive
\[ q_{\text{Radiative}} = \frac{q_{\text{Radiative}}}{\frac{1}{2} \mu u^3} \]

Nonadiabatic
\[ q_{\text{Nonadiabatic}} = \frac{q_{\text{Radiative}}}{1 + \frac{1}{2} \mu u^3} \]

Radiation computation
\textit{NEQAIR} code

References:
Gas Phase Properties

• Thermodynamics
  • Require $C_{p,s}$ ($s =$ species) for air and surface species
    – Must be valid up to 50,000 K (for air) and 6,000 K (for blown species)
    – Must include atoms and their ions (including multiple stages)
    – Must factor in lowering of ionization potential for partition function cut off \( C_{p,s}(p, T) \! \) 
  • $H_s$ and $S_s$ (needed for equilibrium constant) computed from $C_{p,s}$ as
    \[
    \tilde{H}_s(T) = \frac{1}{T} \int_{T_{\text{ref}}}^{T} \tilde{C}_{p,s}(\xi) d\xi \\
    \tilde{S}_s(T) = \int_{T_{\text{ref}}}^{T} \frac{1}{\xi} \tilde{C}_{p,s}(\xi) d\xi \\
    \tilde{C}_{p,s} = \frac{C_{p,s}}{R}, \quad \tilde{H}_s = \frac{H_s}{RT}, \quad \tilde{S}_s = \frac{S_s}{R}
    \]

• Transport
  • Require $\Omega_{i,j}^{(1,1)}$ and $\Omega_{i,j}^{(2,2)}$ ($i,j =$ interacting pairs) up to 50,000 K

• Kinetics
  • Rates for second- and third-stage ionization reactions
    – Charge exchange or electron impact?
Three possible approaches for thermodynamic properties

**Approach #1:** Use LeRC properties
- Linear extrapolation of enthalpy for $T > 20,000$ K $\Rightarrow$ constant specific heat
- No data for higher stages of ionization

**Approach #2:** Use Capitelli *et al.* properties [1] --- included in v4.03 of *DPLR*
- Claimed validity up to $50,000$ K
- Include higher stages of ionization *and* consider ionization potential (IP) lowering
- Include autoionizing states in energy levels

**Approach #3:** Compute properties using NIST energy levels
- Recent work of Johnston *et al.* [2] has thermo properties
  - Includes second stage ionization of N and O, but no partition function cut off
  - IP lowering (dependent on electron number density) included in enthalpy
  - Includes second and third stage of ionization of N and O *and* IP lowering
  - Does not include autoionizing states

**References:**
Thermodynamic Properties (2/2)

- IP lowering reduces number of electronic states included in partition function.
- IP lowering of 1000 cm$^{-1}$ selected for implementation in $DPLR$.
  - Assumed adequate for high-pressure cases (> 1 bar).
- Should pressure dependence be included in math/CFD model?
Flow Characteristics (1/3)

Post-shock temperature \((p_{stag} = 30 \text{ bar})\)

Due to specific heat

Due to second stage ionization

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1\(^{st}\) stage ionization onset

2\(^{nd}\) stage ionization onset
Flow Characteristics (2/3)

- Shock-layer temperature increases with increasing stag. pressure (altitude ↓)
  - Rapid increase up to about 10-30 bar, almost linear thereafter
  - Results based on extrapolated enthalpy past 20,000 K
- Free electron mole fraction decreases with increasing stag. pressure
- Fully-ionized plasma for velocities > 20 km/s
Flow Characteristics (3/3)

- Chemical overshoot at low pressures, between 0.3 and 3 bar
  - Kinetics of second stage ionization needed for high altitudes and velocity > 20 km/s
- Highest shock layer compression at lowest pressure
  - Larger radiating volume at higher pressures
- Without radiation coupling, one would infer blackbody radiation (at low gas emissivity)
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- Without radiation coupling, one would infer blackbody radiation (at low gas emissivity)
• Surface heating completely dominated by shock-layer radiation
  • True across all velocities and hemisphere diameters, except for small (1 m diameter) hemispheres at high altitudes when convection and radiation become comparable

• Radiative heat flux is from Tauber-Wakefield correlation
  • Radiation does not drop rapidly past sonic line attachment (≈40° from stag. point)
• $C_H$ based on hemisphere computations
  • Will be slightly different from full sphere (wake)
  • Peaks at stratopause (roughly)
  • $C_H$ decreases in stratosphere due to exponentially increasing atmospheric density
  • Discrete data curve fit in altitude ($Z$), velocity ($u$), and radius ($R$)
Radiation Energy Deposition (Methodology [1])

- 3 groups of lines of sight
  - nosecap, body, and wake
- Wavelength range
  - 85 nm to 4 μm
- Radiance integrated over *projected* area
  - Area same as pitch plane shock-layer geometry
- Two applications:
  - Near-field radiation energy deposition
  - Transmission through atmosphere to detector 100 km away for magnitude (light curve)

Reference:
Extended Wake

- Wake extended to 48\(D\) for two cases – 12 and 20 km/s, 30 m diameter, and 100 bar stagnation pressure

<table>
<thead>
<tr>
<th>(V/\text{km.s}^{-1})</th>
<th>Wake (L = 6D)</th>
<th>Wake (L = 48D)</th>
<th>Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I/\text{W.sr}^{-1})</td>
<td>12</td>
<td>(1.87 \times 10^{11})</td>
<td>(3.17 \times 10^{11})</td>
</tr>
<tr>
<td>(I/\text{W.sr}^{-1})</td>
<td>20</td>
<td>(5.07 \times 10^{12})</td>
<td>(2.66 \times 10^{13})</td>
</tr>
</tbody>
</table>

Inconclusive without additional expensive calculations
Multiplier probably goes as the square of the velocity
Wall Blowing (1/2)
(V=20 km/s, P=100 bar)
Wall Blowing (2/2)
(Temperature variation of blown air)

<table>
<thead>
<tr>
<th>Case</th>
<th>Mass flux kg.m$^{-2}$.s$^{-1}$</th>
<th>CD</th>
<th>I (wake) W/sr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No blowing, cold wall</td>
<td>0</td>
<td>0.868</td>
<td>1.35 x10$^9$</td>
</tr>
<tr>
<td>No blowing, eq. hot wall</td>
<td>0</td>
<td>0.873</td>
<td>1.21 x10$^9$</td>
</tr>
<tr>
<td>$v_w = 10$ m/s, $T_w = 300$ K</td>
<td>1162.4</td>
<td>0.974</td>
<td>4.56 x10$^8$</td>
</tr>
<tr>
<td>$v_w = 10$ m/s, $T_w = 1000$ K</td>
<td>348.7</td>
<td>0.914</td>
<td>4.68 x10$^8$</td>
</tr>
<tr>
<td>$v_w = 10$ m/s, $T_w = 2000$ K</td>
<td>174.4</td>
<td>0.892</td>
<td>4.68 x10$^8$</td>
</tr>
<tr>
<td>$v_w = 10$ m/s, $T_w = 4000$ K</td>
<td>87.2</td>
<td>0.879</td>
<td>5.75 x10$^8$</td>
</tr>
<tr>
<td>$v_w = 133$ m/s, $T_w = 4000$ K</td>
<td>1162.4</td>
<td>0.952</td>
<td>4.22 x10$^8$</td>
</tr>
</tbody>
</table>

Very little evidence of mixing of blown gas and plasma – turbulence model?
Only wake contribution to intensity shown
Inclusion of blowing reduces radiation from wake
Inclusion of meteoritic species (gas phase only) is possible
Scattering by solid phase has to be developed
Changes in $C_D$ are quite modest – $C_D$ is still O(1) quantity!
Some Open Issues

• Problem formulation might have to be revisited
  • Weakly ionized flow assumption is the basis for current CFD model
• What is the role of pre-cursor (if any) heating?
• Is a two-temperature, $T_{\text{ion}}-T_{\text{electron}}$, formulation needed for the wake?
  – Thermal nonequilibrium is not an issue for the forebody
• Wake closure is an issue, esp. in an axisymmetric formulation
  • 6D is generally used for entry vehicles, but $> 48$D necessary for meteors?
• Line-by-line computations are expensive, esp. for 3D flows
  • Would a Rosseland mean opacity approach be more efficient?
  – High stagnation pressures favor such an approach
  – Can pre-compute opacity tables (including ablation products) using line-by-line method
• Tighter coupling of flow, radiation, and ablation fields
• Ablation models for silicates under development – variation with meteoroid types?
• Transport properties for blown species
• Handling multiple body dynamics
  • Current approach is limited to static arrangements of multiple bodies
Backup
Where we would like to be

Blowing velocity = 0 m/s

Blowing velocity = 10 m/s

Blowing velocity = 133 m/s

Blowing limited to “exposed” faces of the collection of objects
Shock interactions completely altered by blowing